Journal of Environmental Economics and Management 94 (2019) 236–253

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Too hot to handle: The effects of high temperatures during pregnancy on adult welfare outcomes☆

Zihan Hu [a], Teng Li [b,c,*]

[a] Department of Policy Analysis and Management, Department of Economics, Cornell University, USA
[b] Institute of Real Estate Studies, National University of Singapore, Singapore
[c] International School of Business and Finance, Sun Yat-sen University, China

ARTICLE INFO

Article history:
Received 20 February 2018
Revised 21 January 2019
Accepted 22 January 2019
Available online 29 January 2019

JEL classification:
I12
I21
Q51
Q54

Keywords:
Global warming
High temperatures
Prenatal period
Educational attainment
Height

ABSTRACT

This paper studies the long-term effects of high temperatures during pregnancy on later-life outcomes for Chinese adults. Adults experienced one additional high-temperature day during *in utero* period, on average, attain 0.02 fewer years of schooling, increase the risk of illiteracy by 0.18%, achieve lower standardized word-test score by 0.48%, and are shorter by 0.02 cm. The impacts are greater in the first and second trimesters. Additionally, we find that income effects represent one important channel to explain the adverse effects of hot weather. Back-of-the-envelope predictions suggest that by the end of the 21st century, a 0.14–0.54 reduction in years of education and a 0.21–0.84 cm reduction in height is likely to result from climate change, ceteris paribus.

© 2019 Elsevier Inc. All rights reserved.

1. Introduction

A growing literature in economics reveals that hot weather during pregnancy causes negative effects on birth outcomes.[1] An important question that this evidence raises is whether such adverse effects on the birth outcomes further impact adult welfare, and if so, to what extent. Therefore, this study examines the effects of high temperatures on educational attainment and height of Chinese individuals born in rural areas between 1950 and 1994.

The evaluation of the adverse impacts of hot weather is highly relevant in China and other developing countries, which are dominated by rural residents, for two important reasons. First, people in developing countries, especially in rural areas, have

☆ We are grateful to Roger von Haefen (the editor) and two anonymous referees for very helpful comments. We would like thank Sumit Agarwal, Conchita D'Ambrosio, Alice Chen, Yuyu Chen, Junhong Chu, Yongheng Deng, Olivier Deschenes, David Figlio, Sebastian Galiani, John Ham, Rema Hanna, Shanjun Li, Micheal Lovenheim, Bhashkar Mazumder, Jessica Pan, Zhuan Pei, Ivan Png, Daniel Rees, Nicholas Sanders, Slesh Shrestha, Aloysius Siow, Changcheng Song, Heonjae Song, Xi Xiong, Junjian Yi, Klaus Zimmermann, and the numerous seminar participants for providing insightful comments. Any remaining errors are our own.

* Corresponding author. Institute of Real Estate Studies, National University of Singapore, Singapore.
E-mail addresses: zh282@cornell.edu (Z. Hu), irslt@nus.edu.sg, ltsysu1990@gmail.com (T. Li).

[1] Some recent papers that study the adverse effects of high temperatures during pregnancy on birth outcomes include Deschenes et al. (2009), Barreca et al. (2015), and Barreca et al. (2016). See Deschenes (2014) for a comprehensive review.

https://doi.org/10.1016/j.jeem.2019.01.006
0095-0696/© 2019 Elsevier Inc. All rights reserved.

limited access to avoidance behaviors to high temperatures such as air conditioning (Brooks et al., 2005; Feng et al., 2010). Specifically, only 12% of the 689 million rural residents in China owned air conditioning units in 2009 (*China Statistical Yearbook 2010*). In contrast, around 87% of the households in the United States were equipped with at least one air conditioning unit in 2009 (*2009 Residential Energy Consumption Survey*). The limited access to thermal avoidance behaviors may amplify the impacts of high temperatures in the developing world. Second, high temperatures negatively affect crop yields, which represent the main sources of income for rural households. Thus, rural pregnant women might be more vulnerable to high temperatures than their urban counterparts due to the related negative income effects (Schlenker and Roberts, 2009).

According to the National Aeronautics and Space Administration (NASA), the average global temperature at the end of the 21st century are expected to be higher than the levels recorded in the year 2000 by 0.5–8.6 °F (Intergovernmental Panel on Climate Change, 2013). This increase is mainly due to greenhouse gas emissions. Fig. 1 contrasts the daily maximum near-surface air temperature on July 1st of the years 2000 (panel a) and 2100 (panel b) across the world. It shows that the predicted high temperatures can exceed 310 K (around 98 °F) in some places such as China, the Arabian Peninsula, North Africa, and the USA in 2100 if greenhouse gas emissions are not controlled. Thus, the estimation of the costs related to climate change is extremely important to enable policy makers to design effective climate-change-mitigation policies.

To study the effects of hot weather during pregnancy on adult outcomes, we combine individual information from the China Family Panel Studies (CFPS) with weather information from the China Meteorological Administration and the National Oceanic and Atmospheric Administration (NOAA).[2] Exploiting information on the date and place of birth of each individual, we are able to measure the weather conditions during his/her prenatal period. We estimate a model controlling for individual characteristics and a rich set of fixed effects. Our identification relies on plausibly random variations in the temperature distribution for a given county and calendar month.

We find that hot weather during pregnancy triggers significant reductions in adult welfare in multiple dimensions. Specifically, adults who experienced an additional day of high temperature during their prenatal periods, on average, attain 0.02 fewer years of schooling and have a higher risk of illiteracy by 0.18%. Furthermore, these adults show a 0.48% decrease in standardized word-test scores and are shorter by 0.02 cm. The impacts also appear to be concentrated in the first and second trimesters. The effects of high temperatures are not statistically significant in the third trimester.

To the best of our knowledge, such long-term effects on human capital development have not been taken into account in the calculation of the costs of global warming. In the current study, we perform back-of-the-envelope predictions for adult outcomes of individuals who will be born in the rural areas of China in 2100 based on the climate projections provided by the NASA. Compared to those born in 2000, ceteris paribus, individuals who will be born at the end of the 21st century will attain 0.14–0.54 fewer education years and will be shorter by 0.21–0.84 cm.[3]

We propose three hypotheses that may explain why hot weather affects birth outcomes: biological effects, behavioral effects, and income effects. First, pregnant women are more susceptible to ambient heat stress due to the extra physical strain associated with pregnancy. Hence, high temperatures play an important role in determining the fetal size and development by influencing the physical health conditions of pregnant women (see Strand et al. (2011) for a comprehensive review).[4] We refer to these as biological effects. Second, hot weather may induce changes in the daily activities of pregnant women and further affect the birth outcomes. For instance, Herman (1993) documents that ambient heat could reduce appetite and alter food selection, which are critical factors for fetal development (Figlio et al., 2009). We refer to these as behavioral effects. Third, high temperatures affect household resources and nutrition for pregnant women by altering the crop yields, which represent the main source of income in rural areas, and thus impact the health conditions of newborns.[5] We refer to these as income effects.

In this study, we test the existence of income effects by exploiting the variation of the crops sensitivity to heat. We find statistically significant evidence that areas with high proportions of heat-tolerant crops (corn and sugarcane) mitigate the adverse effects of high temperatures during pregnancy. Specifically, when the proportion of heat-tolerant crops reaches about 30%, the adverse effects of hot weather during pregnancy are muted. This evidence suggests that the effects of high temperatures on crop output, and consequently on household income, most likely offer an important explanation for our findings. On the other hand, the existence of biological or behavioral effects cannot be completely ruled out since our data do not include information on the activities of the individuals during pregnancy.

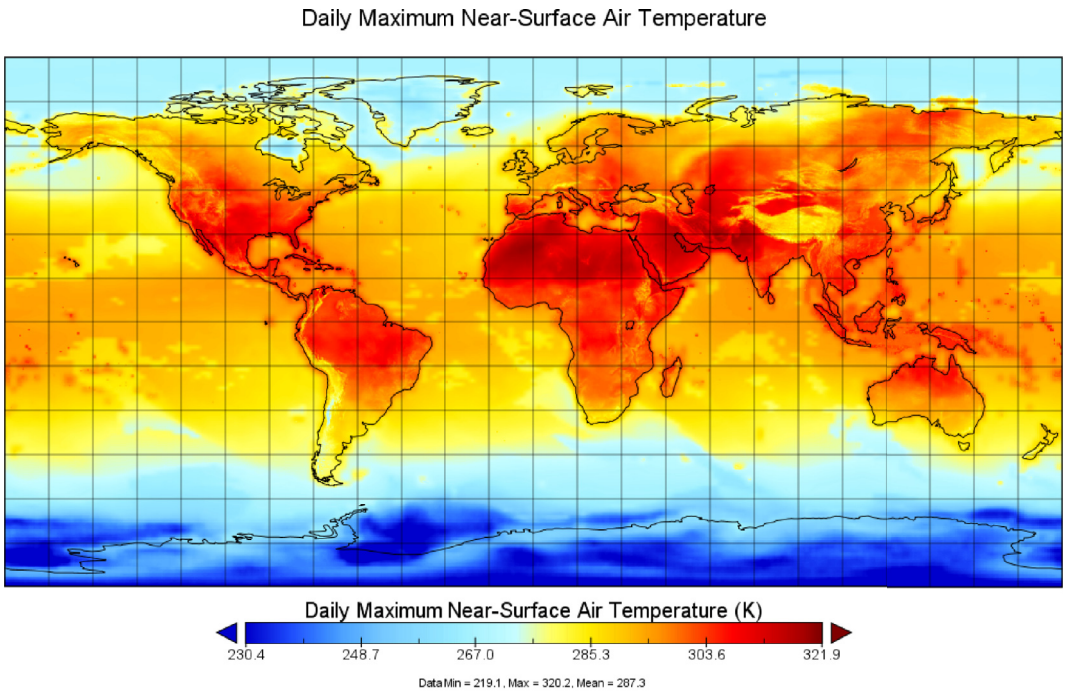
Our paper contributes to the literature in several ways. Deschenes et al. (2009) find that exposure to high temperatures during pregnancy has a modestly negative effect on birth weight. But whether the effect is further related to adult outcomes remains an important but unanswered question. To our knowledge, three papers by Isen et al. (2017), Wilde et al. (2017), and Fishman et al. (2018) study the long-term persistent effects of high temperatures during the prenatal period on adult outcomes. Wilde et al. (2017) show that individuals in sub-Saharan Africa conceived during high temperatures have higher educational

[2] The CFPS is a biennial survey, designed to be complementary to the Panel Study of Income Dynamics (PSID) in the United States. See the data section for details on the CFPS.

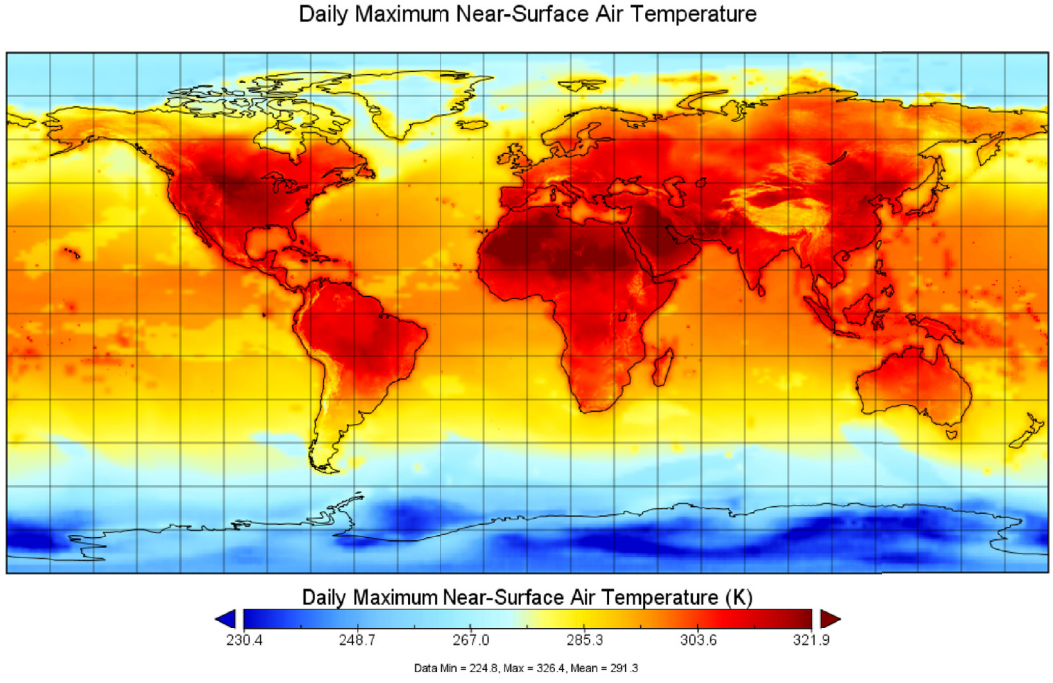
[3] One caveat of our back-of-the-envelope calculations is that we do not take into account that people may adjust their behaviors in the long-run, e.g., moving to other places or adopting adaptive technologies. In other words, our predictions are based on a strong assumption that all other related factors will remain constant, i.e., the same purchasing power, medical technologies, and access to air conditioning.

[4] For details, see the discussion section.

[5] Some recent literature that documents the relationship between high temperatures and crop yield includes Hollinger and Angel (2009), Schlenker and Roberts (2009), and Burgess et al. (2011). For instance, Schlenker and Roberts (2009) find that temperatures above about 85 °F cause damages to corn and soybeans yields.



(a) 2000



(b) 2100

Fig. 1. The global daily maximum near-surface air temperature on the July 1st, 2000 (panel a) and 2100 (panel b).

attainment and literacy due to fetal selection. Isen et al. (2017) employ U.S. data and find that hot weather during pregnancy reduces annual income but does not affect educational attainment. The study of Fishman et al. (2018) shows that 1 °C increase in the average temperature during pregnancy reduces both income and education attainment in Ecuador.

Fig. 2. Provinces covered in the CFPS sample.

In comparison, our study, using China as a developing country context, shows that educational attainment of adults is negatively affected by the *in utero* exposure to high temperatures. In addition to educational attainment, our study examines the effects of high temperatures on physical conditions (height) and advances a detailed discussion of the mechanisms that may explain why hot weather during *in utero* period affects adult welfare. Our findings demonstrate that adverse income changes resulting from hot weather are among the key factor impacting welfare. Our estimates may also offer good external validity to other developing countries. This is because the adverse effects of high temperatures during pregnancy might be highly dependent on the thermal avoidance behaviors and household income sources. Avoidance behaviors can be more costly in the developing world due to the lower quality of housing stock and the more difficult access to air conditioning. Additionally, crop yields as the main source of income in major areas of developing countries could be negatively affected by hot weather. Thus, pregnant women in rural areas might be more vulnerable to high temperatures than the ones in urban areas due to such effects on income.

Second, this paper contributes to a growing literature investigating the relationships between early-life conditions and later-life outcomes (see Currie and Almond (2011) for a comprehensive review). Several influential studies have examined the consequences of early-life shocks, such as the influenza pandemic (Almond, 2006), the Chernobyl disaster (Almond et al., 2009), famine (Chen and Zhou, 2007), and hurricanes (Currie and Rossin-Slater, 2013). These studies reveal that such shocks have persistent and profound effects on well-being in later life. Nevertheless, the unusual nature of these events raises concern about their generalizability to other early-life shocks (Maccini and Yang, 2009; Almond and Mazumder, 2011). Recent investigations have probed the effects of more typical events in early life, such as rainfall (Maccini and Yang, 2009), alcohol availability (Nilsson, 2017), and diet restriction associated with Ramadan fasting (Almond and Mazumder, 2011). We aim to complement this strand of literature by exploring the effects of high temperatures during pregnancy as another typical variation in early-life conditions on later-life outcomes.

Lastly, from a broader perspective, our findings may add to the literature that explains the positive correlation between latitude and economic development. Many scholars have found convincing evidence that economic activities are indirectly correlated with geography through historical channels (see Wacziarg and Spolaore, 2013 for a review). However, some studies provide alternative direct explanations for such phenomena, such as the high burden of disease in addition to the pests and parasites that thrive in hot climates. Based on our findings, we provide another potential explanation: high temperatures affect the newborn endowment, and consequently human capital, which are crucial for economic development.[6]

The rest of this paper is organized as follows. Section 2 describes our data and definitions of the variables. Section 3 introduces the econometric approach. Section 4 presents the main findings. Section 5 discusses the possible channels behind the impacts, implements robustness checks, and predicts the effects of global warming. We conclude in Section 6.

2. Data and descriptive analysis

2.1. Data source

Welfare outcomes. Our major source of data on adult outcomes is the China Family Panel Studies (CFPS) 2010, a nationally representative, annual longitudinal survey of Chinese communities, families, and individuals. The studies were launched in 2010 by the Institute of Social Science Survey (ISSS) of Peking University and cover 25 provinces that represent 95% of the total population of China (Xie, 2012).[7]

Some adult outcomes are included in the survey such as years of schooling, word-test score, and height. Specifically, the interviewers investigated the levels of education of the individuals, which consist of eight categories: illiteracy/semi-illiteracy, primary school, junior middle school, senior middle school, junior college, college, master's degree, and doctoral degree. The years of schooling were then imputed on the basis of the education levels by the survey. The word-test score is also implemented to alternatively measure the educational attainment of the individuals. In the word test designed by the CFPS, respondents are required to read as many Chinese characters as possible.[8] For the sake of interpretation, the score has been standardized in our empirical analyses. Lastly, height is used to reflect the physical conditions of the individuals.

The dataset also provides ample information on demographic status, such as birth year and month, gender, race, county of birth, birth order, number of siblings, and parental characteristics (age, educational attainment, etc.). Based on the birth year and month, we define the prenatal period of each individual as the nine months prior to birth (excluding the birth month), or around 270 days in total.[9] The whole period is typically divided into three trimesters. Socio-economic information may help us capture family heterogeneity across different areas with different climates.[10]

Weather data. Weather data are collected from the China Meteorological Administration and the National Oceanic and Atmospheric Administration (NOAA), including 1509 different weather stations across China. The data set comprises the daily maximum and minimum temperatures in addition to the precipitation. High-temperature days are defined as the number of days with maximum temperatures exceeding 85 °F.[11] To ensure the accuracy of the weather readings, our key variable is defined as the average of the number of high-temperature days of all the weather stations with distances to the county's centroid of less than 80 km and elevations that do not vary by more than 200 m.[12] Hereafter, we simply refer to "high-temperature" or "hot-weather" days. In our sample, a representative rural pregnant woman is exposed to around 53.12 hot-weather days over the total length of pregnancy. Other meteorological controls include the number of low-temperature days and the total precipitation during pregnancy. Low-temperature days are defined as the number of days with daily minimum temperatures below 32 °F.

In the analysis, we restrict our sample to adults born in rural areas, which comprise 84.05% of the original CFPS sample.[13] This restriction is applied for two main reasons. First, individuals in rural areas are more likely to suffer directly from hot weather in general, since they tend to frequently work outdoors and have limited methods to avoid the ambient heat. Second, high

[6] One point worth mentioning is that the negative effects we identify are from transitory temperature shocks. As we do not take into account that people may adjust their behaviors in the long-run (e.g., migration or adaptation behaviors), whether our results can be generalized across latitudes requires further research.

[7] The 25 provinces are Beijing, Tianjin, Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, and Gansu. Fig. 2 shows their geographic distribution.

[8] See the CFPS (2010) user's manual for a detailed description.

[9] The nine-month gestation period is supported by Deschenes et al. (2009). In addition, Patel et al. (2004) find that the median gestational age at delivery is about nine months in Asians. We acknowledge that the prenatal period is inevitably measured with errors since the exact birthdate and gestational length are not available. The classical measurement errors will bias our estimates to zero. Therefore, our estimates provide a lower bound for the effects of high temperatures during pregnancy on adult outcomes.

[10] For instance, Buckles and Hungerman (2013) find that the relationship between season of birth and later outcomes is driven by maternal characteristics.

[11] To test the sensitivity of the estimates to the temperature threshold, we apply different thresholds, ranging from 75 To Whom It May Concern: 90 °F. The adverse impacts on adult outcomes become salient when the threshold is above 80 °F. Results are upon request.

[12] The use of alternative distance thresholds, such as 70 km and 60 km, does not change our main results. Corresponding results are summarized in Tables A.1 and A.2 in appendix.

[13] Adults are defined in this study as the individuals who were at least 18 years old in 2010, consistent with the official definition in China.

Table 1
Summary statistics.

Variable	Mean	Std. Dev.	N
Education Years	6.621	4.139	9024
Illiteracy	0.207	0.405	9024
Word-test Score	0	1	9024
Height (cm)	164.47	7.661	9024
Bottom 10% Height	0.126	0.332	9024
Age	36.863	10.409	9024
Han	0.902	0.297	9024
Female	0.475	0.499	9024
Mother's Education Years	2.242	3.491	9024
Father's Education Years	4.372	4.257	9024
Mother's Age at Birth	27.208	6.142	9024
Father's Age at Birth	29.76	6.909	9024
Birth Order	2.271	1.483	9024
Number of Siblings	2.737	1.75	9024
High Temp Days	53.158	35.938	9024
High Temp Days (1st trimester)	16.872	22.69	9024
High Temp Days (2nd trimester)	17.999	23.024	9024
High Temp Days (3rd trimester)	18.287	23.67	9024
Low Temp Days	60.783	51.254	9024
Low Temp Days (1st trimester)	20.854	29.587	9024
Low Temp Days (2nd trimester)	18.979	28.191	9024
Low Temp Days (3rd trimester)	20.95	29.83	9024
Total Precipitation (log)	6.262	0.911	9024
Total Precipitation(1st trimester,log)	4.789	1.316	9024
Total Precipitation(2nd trimester,log)	4.861	1.284	9024
Total Precipitation(3rd trimester,log)	4.792	1.343	9024

Note: The sample contains 9024 individuals in 141 counties across 25 provinces. All individuals in the sample were born in rural areas. *Illiteracy* is an indicator of illiteracy. *Word-test score* is standardized for convenience of interpretation. *Bottom 10% Height* is an indicator of falling in the bottom 10% of the height distribution. *Age* is the age in years. *Han* is an indicator of being Han race. *Female* is an indicator of being female. *High-temperature days* are defined as those with a daily maximum temperature higher than 85 °F. *Low-temperature days* are defined as the number of days with daily minimum temperatures below 32 °F. *Total Precipitation* measures the logarithm of total precipitation during pregnancy.

temperatures have stronger impact on rural mothers due to the potential adverse effects on their income by damaging crops, which represent the main income sources for rural households.

We also exclude here the individuals whose *in utero* periods overlap with the Chinese famine of 1958–1961. Meng et al. (2015) find that counties with better weather conditions suffered more from the famine due to the government's procurement policy. In other words, high temperatures (bad weather conditions) might have had positive income effects during the famine period, which is not in line with our reasoning. Lastly, observations without exact information about the place of birth are likewise excluded. The remaining sample consists of 9024 individuals in 141 counties across 25 provinces. In our sample, cohort birth years range from 1951 to 1991. In our data set, there are, on average, 244 individuals born in each year. The observations are reasonably evenly distributed across our sample period. Sample statistics are summarized in Table 1.

2.2. Descriptive regional patterns

If ambient heat stress during the prenatal period is an important determinant of long term welfare outcomes, we can expect the individuals in warmer regions to have worse adult outcomes on average. In this subsection, we depict the relationships between temperature and adult outcomes across provinces.[14]

Panels (a) through (d) in Fig. 3 plot the mean years of schooling, illiteracy, word-test score, and height, respectively, against the number of hot-weather days (> 85 °F) for a representative gestational period across provinces.[15] Compared to the southern provinces (blue circle markers in Fig. 3), provinces in the north (red square markers) suffer less frequently from hot weather.[16] The four figures indicate that hot weather during pregnancy might further be related to welfare losses in adulthood. Specifically, Panels (a)-(c) display interesting regional patterns showing that adults born in warmer places (lower latitudes in general) man-

[14] Importantly, the correlations depicted below only serve as the motivation for this project. They do not imply any causal interpretations. They could be explained by other factors. For instance, Northern Chinese are on average taller than Southern Chinese, and this might be explained by the differences in cuisine or genetics, rather than the differences in temperatures.

[15] Beijing is excluded from these panels, since the average years of schooling and word- and math-test scores for individuals are far beyond those in other provinces.

[16] We use an official geographical dividing line—the Huai River-Qin Mountains—to define the northern and southern provinces in China.

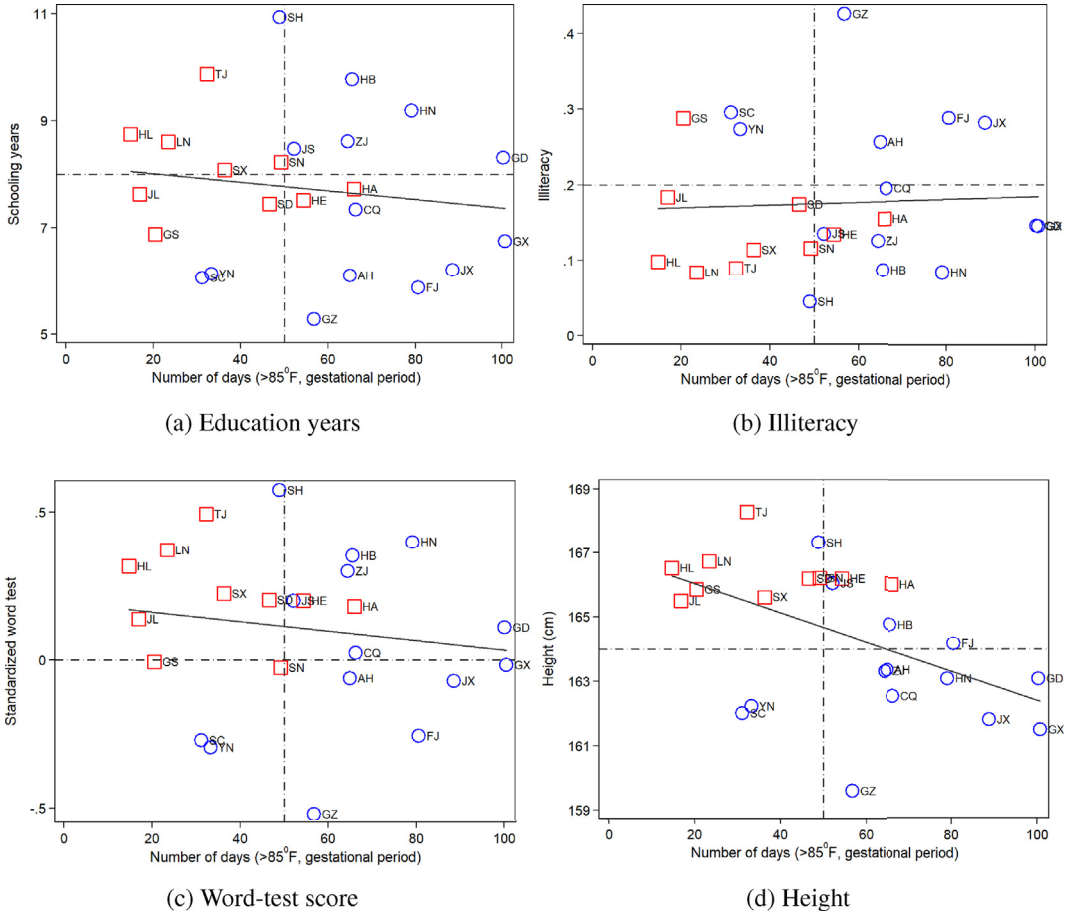


Fig. 3. Adult outcomes against number of high-temperature days (> 85 °F) for a typical gestational period by province. Note: Red square and blue circle markers represent provinces in the north and south, respectively. The solid line is fitted using OLS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ifest fewer schooling years, higher risk of illiteracy, and lower word-test scores. Panel (d) shows the same regional pattern that the warmer the area, the shorter the height is, a phenomenon in China also documented by Buxton (2013). Our findings suggest that the high temperatures during pregnancy may explain this geographical distribution of height to some extent.

3. Empirical framework

To identify the causal effect of high-temperature exposure during pregnancy on adult outcomes, our model relies on plausibly random variations in the temperature distribution for a given county and calendar month. To partial out potential confounding factors, we exploit the panel nature of our data to account for unobserved differences in counties, months, and years by estimating the following specification:

$$Y_{icmy} = \beta HighTemp_{icmy} + W'_{icmy}\gamma + X'_i\delta + county_c \times year_y + county_c \times month_m + month_m \times year_y + \epsilon_{icmy}. \quad (1)$$

Here, i refers individuals, c represents counties, and the birth month and year are denoted by m and y, respectively. The dependent variables, Y_{icmy}, are the adult outcomes, including schooling years, illiteracy, standardized word–test score, and height. The variable of interest in Eq. (1) is $HighTemp_{icmy}$, which is the number of hot-weather days during the gestational period. Other meteorological factors (W_{icmy}), such as the number of cold-weather days and total precipitation (mm, in logarithm) during the gestational period are controlled. We add a vector of individual characteristics, X_i, including gender, race, birth order, number of siblings, parental age at delivery, and parental educational attainment, in order to capture the individual heterogeneity.[17]

[17] As the number of high temperature days during pregnancy is not correlated with demographic characteristics, adding demographic control variables in the regression model should only increase the precision. We find that the estimates without demographic controls are both qualitatively and quantitatively comparable to those with demographic controls. The results are upon request.

Table 2
Balanced check on observable characteristics.

Dependent Variable:	(1) Female	(2) Han	(3) ME	(4) MA	(5) FE	(6) FA	(7) Birth Order	(8) No. of Siblings
High Temp Days	−0.0003	−0.0005	0.0005	0.0116	−0.0017	0.0140	0.0068*	0.0001
	(0.0005)	(0.0015)	(0.0094)	(0.0125)	(0.0189)	(0.0196)	(0.0036)	(0.0043)
Low Temp Days	0.0010	0.0025	0.0028	0.0168	−0.0413*	−0.0222	−0.0088	−0.0006
	(0.0007)	(0.0024)	(0.0142)	(0.0175)	(0.0232)	(0.0303)	(0.0062)	(0.0074)
Precipitation (log)	−0.0074	0.0008	0.2500	0.0369	−0.2073	0.0680	−0.0901	−0.0218
	(0.0062)	(0.0250)	(0.1966)	(0.1820)	(0.3113)	(0.3351)	(0.0631)	(0.0716)
County-Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	9024	9024	9024	9024	9024	9024	9024	9024
R-Squared	0.807	0.542	0.664	0.657	0.570	0.576	0.604	0.723

Note: The dependent variables in columns (1)–(6) are female dummy, Han race dummy, and mother's education years and age at birth and father's education years and age at birth, respectively. An observation is an individual born in a rural area. High- and low-temperature days are defined as those with daily maximum temperatures higher than 85 °F and with daily minimum temperatures lower than 32 °F. Ordinary least squares estimates for all columns. Standard errors in parentheses, clustered by county. *** Significant at 1%, ** significant at 5%, * significant at 10%.

To isolate the causal effect, the specification includes all of the three sets of two-way fixed effects, i.e., county-by-year, county-by-month, and year-by-month fixed effects: (1) County-by-year fixed effects could capture the nonlinear changes in the determinants of the human capital formation. China enacted several policies during our sample period such as the collectivization of land (in the late 1950s), the Cultural Revolution (1966–1976), and the 9-year Compulsory Education (1986). Thus, these effects might create nonlinear region-specific differences over time and need to be taken accounted by the county-by-year fixed effects; (2) County-by-month fixed effects account for permanent unobserved county-by-month factors that might be correlated with both temperature and early-life health such as seasonal employment. These fixed effects ensure that our model is identified from the presumed random annual fluctuations in the distribution of temperatures in a given county and calendar month; (3) Year-by-month fixed effects capture the year-specific seasonal shocks that are common to all counties.

ϵ_{icmy} denotes an idiosyncratic random error term. In our main results, standard errors are clustered at the county level. To allow for potential temporal and spatial autocorrelations, we use a number of other methods for inferences, including clustering at the province level (bootstrap-based), two-way clustering (county and year), and spatial clustering (Cameron et al. 2008, 2011; Hsiang, 2010; Barrios et al., 2012). Table A.3 shows that the inferences change slightly.

As suggested by the epidemiological literature, ambient environment in different trimesters may have heterogeneous effects on birth weight and adult outcomes. In the following specification, we allow for such heterogeneity:

$$Y_{icmy} = \sum_{T=1}^{3} \beta^T HighTemp_{icmy}^T + \sum_{T=1}^{3} \gamma^T W_{icmy}'^T + X_i'\delta + county_c \times year_y + county_c \times month_m + month_m \times year_y + \epsilon_{icmy}, \quad (2)$$

where $HighTemp_{icmy}^T$ denotes the number of hot-weather days in each trimester. $T = 1$, 2, and 3 denote the first, second, and third trimester, respectively. W_{icmy}^T consists of the number of cold-weather days and the total precipitation in each trimester. The other notations are the same as those in Eq. (1).

4. Main results

This section reports the estimated effects of ambient heat stress during pregnancy on the later-life well-being, including the educational attainment and height. Moreover, the heterogeneous effects of high temperatures on all outcomes across trimesters, family background, and birth place are outlined.

Before proceeding to report our major findings, we first validate our main specification. Specifically, we regress the personal characteristics on high-temperature days during pregnancy including the sets of fixed effects in Eq. (1). If high-temperature days are not associated with the observable characteristics conditional on the sets of fixed effects, it would support the exogeneity of high-temperature days in our main specification. The results in Table 2 demonstrate that except for birth order, all the coefficients of high-temperature days are neither economically nor statistically significant at the traditional level. Hence, the results indicates that the high-temperature days are not correlated with any observable characteristics conditional on the sets of fixed effects. This finding suggests that the high-temperature days in our main specification are exogenous. In addition, we also find that most coefficients on low-temperature days and precipitation are not statistically significant.[18]

[18] Column (1) in Table 2 indicates that there is no significant sex selection induced by hot weather during pregnancy. Otherwise, sex selection may bias our estimates downwards. In contrast, Wilde et al. (2017) find that because of fetal selections in Sub-Saharan African, the hot weather around the time of conception induces better educational attainment later in life and lowers child mortality.

Table 3
The impact of high temperatures during pregnancy on adult outcomes.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days	−0.0157*	0.0018**	−0.0048**	−0.0235*	0.0016**
	(0.0093)	(0.0009)	(0.0022)	(0.0141)	(0.0008)
Low Temp Days	−0.0000	−0.0014	0.0021	0.0172	−0.0008
	(0.0156)	(0.0016)	(0.0037)	(0.0245)	(0.0015)
Precipitation (log)	0.0286	0.0036	−0.0360	−0.0058	−0.0201
	(0.1853)	(0.0218)	(0.0492)	(0.3452)	(0.0170)
Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year FE	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	9024	9024	9024	9024	9024
R-Squared	0.715	0.657	0.705	0.796	0.620

Note: An observation is an individual born in a rural area. High- and low-temperature days are defined as those with daily maximum temperatures higher than 85 °F and with daily minimum temperatures lower than 32 °F. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates for all columns. Standard errors in parentheses, clustered by county. ** Significant at 1%, ** significant at 5%, * significant at 10%.

4.1. Effects on adult outcomes

Next, we begin our analysis by presenting the effects of ambient heat during pregnancy on adult outcomes, shown in Table 3.[19] All the columns include the supplementary weather controls, the personal characteristics, and the three sets of two-way fixed effects.

Educational Attainment. We present here the effect of ambient heat during pregnancy on educational outcomes, including the education years, the risk of illiteracy, and the standardized word-test score. Column (1) shows that the effect of high temperatures during pregnancy on education years is negative and statistically significant at the 7% level. The coefficient indicates that one additional high-temperature day lowers the average years of schooling by 0.02 years. From another perspective in column (2), we find that hot weather in the prenatal period leads to a statistically significant increase in the risk of illiteracy. One additional high-temperature day increases the risk of illiteracy by 0.18 percentage points. In column (3), we examine the adverse effects of hot weather on the standardized word-test score. The point estimate indicates that adults who experienced one more high-temperature day in the prenatal period have 0.48% lower standardized word-test score and the effect is statistically significant at the 5% level.

We also notice that cold weather and precipitation do not have statistically significant effects on the education years, the risk of illiteracy, or on the standardized word-test score. Furthermore, males and individuals whose parents have higher educational achievements tend to have longer years of schooling. Younger children in one family are less likely to be illiteracy, in agreement with the findings of Black et al. (2005).

Height. Column (4) in Table 3 shows the impact of ambient heat during pregnancy on height. The coefficient implies that hot weather during pregnancy has a statistically significant effect on height. The point estimate shows that one additional high-temperature day lowers the average height by 0.02 cm. Similar to the analyses on educational attainment, we also generate a dummy indicating that an adult's height falls in the bottom 10% of the sample distribution. The estimate exhibits that one more high-temperature day in the prenatal period statistically significantly increases the risk of falling in the bottom 10% for height by 0.16 percentage points.

4.2. Trimester heterogeneity

In this subsection, we attempt to explore the heterogeneous effects of ambient heat across the trimesters of pregnancy. Table 4 illustrates the effects of high temperatures in each trimester. In each regression, we include all the supplementary weather controls, the personal demographic characteristics, and the three sets of two-way fixed effects. Columns (1) through (5) present the results for the adult outcomes.

Noticeably, the adverse effects of hot weather in the second trimester are more statistically significant and are larger for all the educational outcomes.[20] Precisely, individuals who were exposed to one additional high-temperature day in the second trimester encounter 0.02 fewer education years, 0.32% higher risk of illiteracy, and 0.55% decrease in standardized word-test score. On the other hand, the effects in both the first and second trimesters are more pronounced for height. Individuals who were exposed to one more high-temperature day in the first and second trimesters are 0.06 and 0.04 cm shorter, respectively.

[19] Individuals who did not survive due to exposure to ambient heat in the prenatal period are not included in our sample. The welfare losses might be underestimated because of this selection (Black et al., 2007).

[20] Although the coefficients for education years are not statistically significant at the traditional level, we conduct a Wald test which shows that the overall effect of the high temperatures during the three trimesters on education years is statistically significant at the 10% level.

Table 4
The impacts of high temperatures during pregnancy on adult outcomes by trimester.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days (1st trimester)	−0.0165	0.0026*	−0.0043	−0.0557**	0.0039***
	(0.0144)	(0.0014)	(0.0035)	(0.0251)	(0.0014)
High Temp Days (2nd trimester)	−0.0178	0.0032**	−0.0055*	−0.0422**	0.0003
	(0.0132)	(0.0013)	(0.0031)	(0.0207)	(0.0013)
High Temp Days (3rd trimester)	−0.0150	0.0004	−0.0049	0.0296	0.0009
	(0.0144)	(0.0015)	(0.0035)	(0.0219)	(0.0012)
Weather & Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	9024	9024	9024	9024	9024
R-Squared	0.716	0.658	0.706	0.796	0.622

Note: An observation is an individual born in a rural area. High-temperature days are defined as those with daily maximum temperatures higher than 85 °F. Each trimester consists of three months. Weather controls include the number of low-temperature days and total precipitation during pregnancy. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates. Standard errors in parentheses, clustered by county. *** Significant at 1%, ** significant at 5%, * significant at 10%.

Table 5
Heterogeneous effect by parental education.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days	−0.0132	0.0015	−0.0039*	−0.0201	0.0014*
	(0.0101)	(0.0009)	(0.0023)	(0.0143)	(0.0008)
High Temp Days × Father's Education Years	−0.0004	0.0000	−0.0002*	−0.0004	0.0000
	(0.0005)	(0.0000)	(0.0001)	(0.0006)	(0.0000)
High Temp Days × Mother's Education Years	−0.0002	0.0000	0.0000	−0.0007	0.0000
	(0.0005)	(0.0001)	(0.0001)	(0.0008)	(0.0000)
Father's Education Years	0.1878***	−0.0135***	0.0475***	0.0311	−0.0028
	(0.0296)	(0.0029)	(0.0079)	(0.0445)	(0.0026)
Mother's Education Years	0.1148***	−0.0062*	0.0135	0.0686	−0.0012
	(0.0346)	(0.0033)	(0.0096)	(0.0606)	(0.0026)
Weather & Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	9024	9024	9024	9024	9024
R-Squared	0.715	0.657	0.706	0.796	0.620

Note: An observation is an individual born in a rural area. High-temperature days are defined as those with daily maximum temperatures higher than 85 °F. Weather controls include the number of low-temperature days and total precipitation during pregnancy. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates for all columns. Standard errors in parentheses, clustered by county. *** Significant at 1%, ** significant at 5%, * significant at 10%.

However, high temperatures in the third trimester do not have statistically significant effects on these adult outcomes. Such sensitivity to temperature fluctuations during the first and second trimesters has also been documented by multiple papers in medical research (Murray et al., 2000; Elter et al., 2004). Since our data do not enclose the precise birth date or gestational length, trimesters could be defined with some errors. Therefore, we cautiously conclude that pregnant women are more sensitive to ambient heat in the first two trimesters.

4.3. Heterogeneous effects across family background and birth place

First, we examine the heterogeneous effects of high temperatures during pregnancy across individuals with different family backgrounds. Specifically, we add an interaction term between the parents' years of education and the number of hot-weather days in Eq. (1). As can be seen in Table 5, the interaction terms are not statistically significant across the outcomes. These results suggest that there is no significant difference in adaptive resources (e.g., quality of housing stock) across families during our sample period.

Next, we examine the heterogeneous effects of high temperatures during pregnancy for the rural- and urban-born individuals.[21] We estimate the model with the interaction between high-temperature days during pregnancy and a rural-born dummy variable. The results are presented in Table A.4. As can be seen, the coefficients of the high-temperature days during pregnancy are relatively small and insignificant, indicating that urban-born individuals are less affected by hot weather during pregnancy.

[21] Urban-born individuals occupy a relatively small proportion (15.95%) in the CFPS.

Table 6
Does a high proportion of heat-tolerant crops mitigate the adverse effects of high temperatures during pregnancy on adult outcomes?.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days	−0.0310***	0.0034**	−0.0091***	−0.0517**	0.0035***
	(0.0118)	(0.0013)	(0.0033)	(0.0210)	(0.0013)
High Temp Days X C4	0.0011*	−0.0001*	0.0003	0.0018*	−0.0001**
	(0.0006)	(0.0001)	(0.0002)	(0.0010)	(0.0001)
Weather & Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year FE	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	9005	9005	9005	9005	9005
R-Squared	0.715	0.657	0.705	0.796	0.621

Note: An observation is an individual born in a rural area. C4 Plant Area represents corn and sugarcane proportion of crop acreage within the province. High-temperature days are defined as those with daily maximum temperatures higher than 85 °F. 19 observations are missing from the main regression sample, because crop-area information is missing for Shanghai in 1993. Weather controls include the number of low-temperature days and total precipitation during pregnancy. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates. Standard errors in parentheses, clustered by county. *** Significant at 1%, ** significant at 5%, * significant at 10%.

Additionally, the coefficients of the interactions are statistically significant for the risk of illiteracy and height. Although the coefficients of the interactions are not statistically significant for schooling years or word-test scores, their signs are negative. These results suggest that the effects of hot weather during pregnancy are more salient for rural-born individuals than their urban-born counterparts.

A possible explanation could be that the living conditions, such as the housing quality and availability of cooling tools, in urban areas are considerably better than those in rural areas. Moreover, pregnant women in rural China are exposed to ambient heat more frequently and directly than their urban counterparts (Peterman et al., 2013).[22] Furthermore, urban mothers' household income is less affected by the adverse effect of high temperatures on crop yields, as they are not the main income source for urban households. Therefore, we will focus on the rural sample henceforth.

5. Discussion

5.1. Mechanisms

Our results have thus presented the effects of high temperatures during pregnancy on adult outcomes. Several channels may account for such impacts. One possibility is that hot weather has adverse physiological influences on pregnant women due to the associated physical and mental strain.[23] Heat stress triggers negative impacts on newborns such as low birth weight by affecting the health of the pregnant women. In addition to biological effects, hot weather may induce changes in daily activities (behavioral effects). For instance, Herman (1993) documents that ambient heat could reduce appetite and alter food selection. Food intake and selection are critical for fetal development. Furthermore, high temperatures may also cause damage to crop yields (Hollinger and Angel, 2009; Schlenker and Roberts, 2009; Burgess et al., 2011), which decide the family resources in rural areas and thus influence the endowment of newborns (Maccini and Yang, 2009). Since the data do not enclose information on the individual activities during pregnancy, we cannot test the existence of biological or behavioral effects.

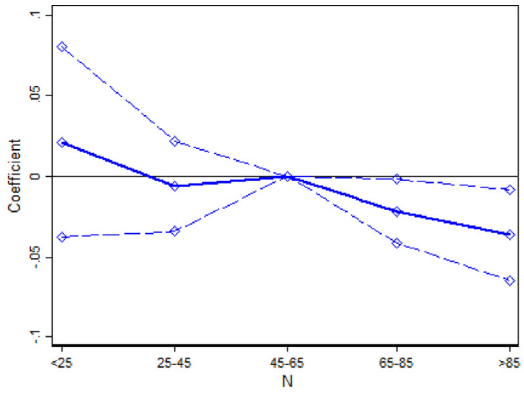
We can, however, test the channel of income effects. To accomplish this, we exploit the variation of sensitivity of crops to heat. Hollinger and Angel (2009) reveal that heat stress is more likely to cause damage to crops when the temperatures approach or exceed 85 °F. Moreover, the mode of the response of crops to hot weather varies. Specifically, C4 plants, including corn, sugarcane, and sorghum, are more adaptable to hot weather due to the efficient way they retain water in a hot environment. In contrast, C3 plants (barley, rice, wheat, etc.) are more sensitive to heat stress. If income effects constitute an important factor, high temperatures during pregnancy will have a smaller effect on people living in areas of abundant cultivation of C4 plants and a major effect on those in the areas of C3 plants. To test the income channel, we employ the following specification:

$$Y_{icmy} = \beta HighTemp_{icmy} + \zeta C4PlantArea_{py} + \kappa HighTemp_{icmy} * C4PlantArea_{py} + W'_{icmy}\gamma + X'_i\delta + +county_c \times year_y + county_c \times month_m + month_m \times year_y + \epsilon_{icmy}. \quad (3)$$

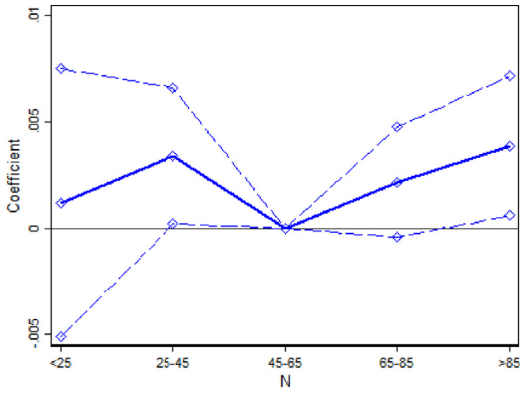
Here, p refers to provinces. $HighTemp_{icmy}$ denotes the number of days with a daily maximum temperature higher than 85 °F during pregnancy. $C4PlantArea_{pt}$ represents the proportion of corn and sugarcane of the crop acreage within each province-

[22] Peterman et al. (2013) employ the time use data and find that time spent by pregnant women in rural China on agricultural jobs is not statistically significantly different from that spent by non-pregnant women.

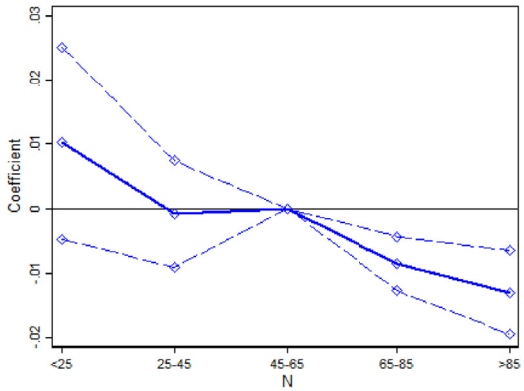
[23] Strand et al. (2011) suggest that a pregnant woman may be sensitive to heat stress because (i) the capacity to lose heat by sweating is lessened due to the reduced ratio of surface area to body mass, (ii) weight gain triggers more heat production, (iii) core temperature increases with accumulated fat deposition, and (iv) the increased body composition and metabolic rate of the fetus cause a rise in maternal heat stress.



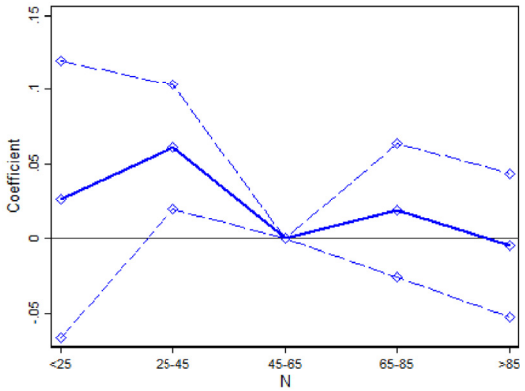
(a) Schooling years



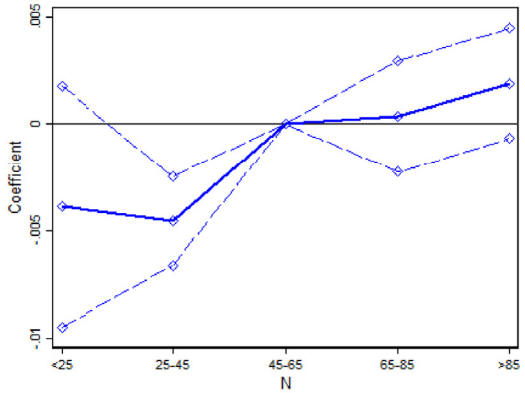
(b) Illiteracy



(c) Word-test score



(d) Height



(e) Height in Bottom 10%

Fig. 4. Non-linear impacts of temperature exposure during pregnancy on adult outcomes, estimated by temperature-bin approach. Note: The solid line denotes the estimated coefficients on each temperature bin. Dash lines represent the upper and lower bounds for the 95% confidence interval. The temperature bin 45–65 °F is normalized to zero. The regressions control for other weather conditions, demographic characteristics, county-by-year, county-by-month, and year-by-month fixed effects.

Table 7
The impacts of high temperatures by periods on adult outcomes.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
3 Months Before Conception	0.0224	−0.0014	0.0041	0.0382	−0.0021
	(0.0183)	(0.0021)	(0.0043)	(0.0249)	(0.0016)
1st Trimester	−0.0185	0.0026*	−0.0037	−0.0513*	0.0038***
	(0.0154)	(0.0016)	(0.0038)	(0.0260)	(0.0014)
2nd Trimester	−0.0271*	0.0039***	−0.0065*	−0.0567**	0.0008
	(0.0146)	(0.0015)	(0.0036)	(0.0244)	(0.0015)
3rd Trimester	−0.0270	0.0012	−0.0076*	0.0009	0.0019
	(0.0178)	(0.0018)	(0.0041)	(0.0277)	(0.0014)
0–3 Months After Birth	−0.0149	0.0011	−0.0037	−0.0539*	0.0027
	(0.0184)	(0.0018)	(0.0049)	(0.0296)	(0.0018)
3–6 Months After Birth	−0.0075	0.0012	−0.0052	−0.0332	−0.0004
	(0.0181)	(0.0018)	(0.0047)	(0.0289)	(0.0014)
6–9 Months After Birth	0.0091	−0.0003	−0.0004	0.0342	−0.0007
	(0.0167)	(0.0019)	(0.0039)	(0.0236)	(0.0015)
Weather & Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	8985	8985	8985	8985	8985
R-Squared	0.716	0.658	0.706	0.796	0.622

Note: An observation is an individual born in a rural area. High-temperature days are defined as those with daily maximum temperatures higher than 85 °F. Nine months before conception is defined as ten to eighteen months before birth. 39(=9024–8985) individuals in our sample do not have weather information in three months before conception. Weather controls include the number of low-temperature days and total precipitation during pregnancy. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates. Standard errors in parentheses, clustered by county. *** Significant at 1%, ** significant at 5%, * significant at 10%.

year cell.[24] The other notations are the same as those in Eq. (1). If high temperatures affect people through the income channel, we expect the coefficient of the interaction term κ to be significantly positive. As shown in Table 6, the interaction terms are statistically significantly positive for most outcomes. When the proportion of heat-tolerant crops approaches 30%, the adverse effects of hot weather during pregnancy are muted.[25] These results provide support for the existence of income effects even though biological and behavioral effects cannot be ruled out completely, and may even play a larger role.

5.2. Nonlinear effects of hot weather

This subsection describes the investigation of the nonlinear effects of temperatures on adult outcomes. Following Deschenes et al. (2009), we use the 20-degree temperature-bin approach to investigate the non-linear effects of temperatures during the pregnancy period. The results are graphically summarized in Fig. 4. In line with Deschenes et al. (2009), we also use 45–65 °F as the reference group. The coefficients displayed in Panels (a)-(e) of Fig. 4 measure the impacts of one additional day of a specific temperature group on the outcomes of interest, relative to that of a day between 45 °F and 65 °F. The 95% confidence intervals associated with the estimates are plotted in the figures as well.

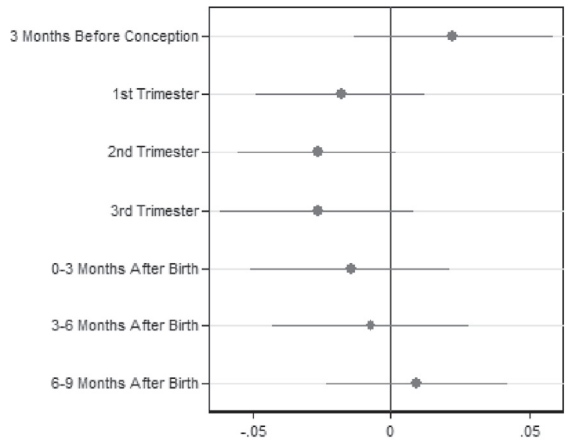
As shown in Fig. 4, the coefficients are reasonably monotonic with the increasing temperature bins. Specifically, exposure to one additional day with 85 °F or above during pregnancy period is associated with a statistically significant adverse effect on education years and word test scores, and a higher risk of illiteracy and falling in the bottom 10% of the height. Moreover, for most of the dependent variables, one additional day between 65 °F and 85 °F has the same direction effects, but with smaller magnitudes. These results indicate at which temperatures the effects are most profound.

5.3. Effects of high temperatures before conception and after birth

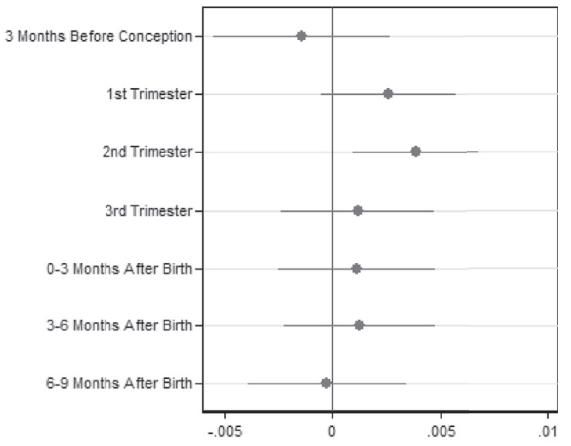
In Table 7, we simultaneously control the weather conditions before conception, during pregnancy, and after birth. The coefficients and confidence intervals are plotted in Fig. 5. In general, adult outcomes should not be influenced by temperatures before conception. The results in the first row confirm this hypothesis since the effects of high temperatures during the

[24] Data on county-level plant area before 1997 are not available. Instead, we use plant-area data from the Thematic Database for Human-earth System (http://www.data.ac.cn/zrzy/DH55.asp?name-=&pass=&danwei=). It provides the plant area of each crop within each province from 1949 till 2000. There are two C4 crops (corn and sugarcane) in the dataset; the other 8 crops are C3 plants.

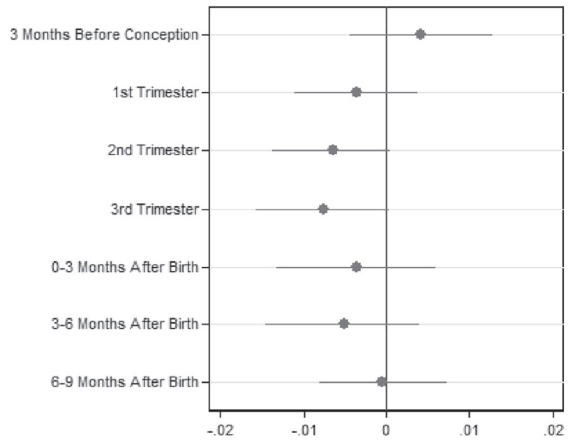
[25] On average, the proportion of C4 crops is 13.30% in our sample. One standard deviation is 9.11%.



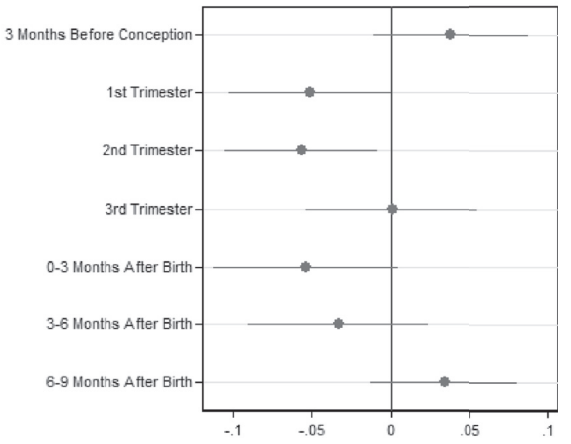
(a) Schooling years



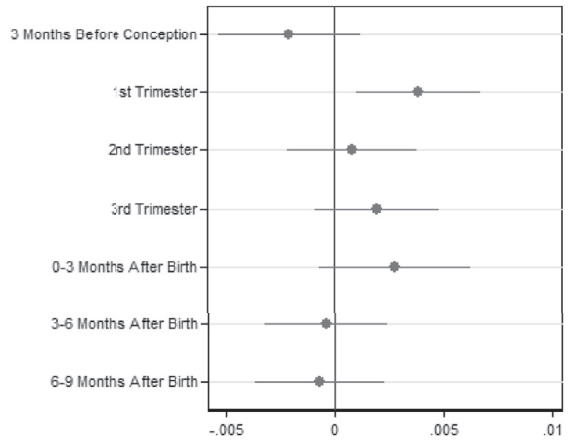
(b) Illiteracy



(c) Word-test score



(d) Height



(e) Height in Bottom 10%

Fig. 5. Coefficients of high-temperature days by periods. Note: Dots denote the estimated coefficients on each variable. Solid lines represent the 95% confidence interval. The regressions control for other weather conditions, demographic characteristics, county-by-year, county-by-month, and year-by-month fixed effects.

three months prior to conception are not statistically significant at the traditional level. Similar to the estimates in Table 4, the results in the second to the fourth rows indicate that the adverse impacts of high temperatures during pregnancy are concentrated in the first and second trimesters. Alongside the *in utero* stage, the early-life conditions after birth may also be critical for human capital development (Almond et al., 2009). In the fifth to the seventh rows, we find that high temperatures after birth do not statistically significantly affect adult outcomes. One exception is that hot weather in the first three months after birth statistically significantly influences height. Moreover, the magnitude is similar to those in the first and second trimester during pregnancy. Broadly, the adverse effects of hot weather during the *in utero* period are salient in comparison to other periods.

5.4. Predicting the impacts of climate change on adult outcomes

In previous literature, the effects of high temperatures during pregnancy have not been taken into account when calculating the costs of global warming. Based on the climate projections provided by NASA, we perform back-of-the-envelope predictions for adult outcomes of individuals who will be born in rural areas of China in 2100. Our predictions strongly rely on the assumption that all other related factors will remain constant. We acknowledge that individuals can adapt to changing environment and mitigate the potential negative effects of increasing temperatures. Moreover, the access to air conditioning has been dramatically increasing in China and other developing countries in recent years. Nevertheless, the back-of-the-envelope predictions here can provide us with a concrete figure that articulates the specific effects of global warming without accounting for the potential progress of technology and the probable adaptation processes.

Assuming that greenhouse gas emissions will peak around 2040 (RCP 4.5 scenario), we predict that, holding all else equal, adults born in rural areas of China in 2100, on average, will incur 0.14 fewer years of schooling and 0.21 cm decrease in height, compared to those born in 2000 due to global warming.[26] In a more pessimistic scenario (RCP 8.5 scenario), greenhouse gas emissions will peak around 2100.[27] Likewise, the reductions in education years and height will increase to 0.54 years and 0.84 cm, respectively. It should be noted once more that the above predictions are based on a strong assumption that all other related factors will remain constant—i.e., the same purchasing power, medical technologies, and access to air conditioning (Barreca et al., 2016; Zivin et al., 2015). Since other factors are being improved in China especially in rural areas, the effects of global warming are likely to not be as pronounced as these forecasts suggest.

6. Conclusions

In this paper, we examine the long-term effects of high temperatures during the prenatal period on education attainment and height. Our results indicate that hot weather in early life has persistent and profound effects in later life. By enduring one more hot-weather day *in utero*, individuals attain 0.02 fewer years of schooling, increase the risk of illiteracy by 0.18%, show 0.48% lower standardized word-test score, and are shorter by 0.02 cm. The impacts seem to be concentrated in the first and second trimesters. We also examine the possible mechanisms behind the adverse effects of hot weather during pregnancy. The results indicate that the income effects are one important channel through which high temperatures during pregnancy affect the adult outcomes.

The adverse effects of high temperatures during pregnancy have not been taken into account when calculating the costs of global warming. Our back-of-the-envelope predictions suggest that at the end of the 21st century, ceteris paribus, adults born in rural China on average will incur 0.14–0.54 years decrease of schooling and 0.21–0.84 cm decreases in height, respectively, compared to those born in 2000.

Our results also demonstrate that income effects represent one important channel to explain the adverse effects of hot weather. This finding has important policy implications, as it justifies the interventions that provide necessary nutrition to pregnant women. The interventions may protect their children from adverse cognitive and/or health consequences.

In this study, due to limits of the data, we are not able to examine physiological or behavioral effects caused by hot weather during pregnancy. Exploring physiological and behavioral effects in addition to income effects and examining to what extent they can explain the negative effects of high temperatures during pregnancy are critical for future research.

Disclosure statement

The authors declare that they have no relevant or material financial interests that relate to the research described in this paper. The paper's dataset can be disclosed.

[26] RCPs are possible greenhouse-gas-concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC). Specifically, RCP 4.5 presumes that global annual greenhouse gas emissions (measured in CO2-equivalents) will peak around 2040, then decrease. In RCP 8.5, emissions keep increasing throughout the 21st century. Under the RCP 4.5 scenario, the number of high-temperature days during pregnancy increases by 12.35 days on average. As cold weather in the analysis does not have significant effects on most outcomes, it is not taken into account in this back-of-the-envelope predictions.

[27] Under the RCP 8.5 scenario, the number of high-temperature days during pregnancy increases by 47.87 days on average.

A. Appendix

Table A.1
Robustness checks of the impacts of high temperatures on all outcomes using weather stations within 70 km radius.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days	−0.0203*	0.0018*	−0.0045*	−0.0257*	0.0013
	(0.0117)	(0.0010)	(0.0026)	(0.0143)	(0.0009)
Low Temp Days	0.0038	−0.0017	0.0069	0.0198	−0.0006
	(0.0174)	(0.0018)	(0.0045)	(0.0283)	(0.0017)
Precipitation (log)	0.2346	−0.0090	0.0115	0.0659	−0.0407*
	(0.2631)	(0.0344)	(0.0732)	(0.4347)	(0.0206)
Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year FE	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	7257	7257	7257	7257	7257
R-Squared	0.732	0.674	0.715	0.811	0.643

Note: An observation is an individual born in a rural area. Each county is matched to all weather stations within 70 km. High- and low-temperature days are defined as those with daily maximum temperatures higher than 85 °F and with daily minimum temperatures lower than 32 °F during the eight months before birth. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates for all columns. Standard errors in parentheses, clustered by county. ***Significant at 1%, **significant at 5%, *significant at 10%.

Table A.2
Robustness checks of the impacts of high temperatures on all outcomes using weather stations within 60 km radius.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days	−0.0141	0.0017**	−0.0047**	−0.0255*	0.0013*
	(0.0096)	(0.0008)	(0.0023)	(0.0142)	(0.0007)
Low Temp Days	0.0049	−0.0011	0.0043	0.0108	−0.0011
	(0.0162)	(0.0017)	(0.0039)	(0.0251)	(0.0016)
Precipitation (log)	0.1853	−0.0115	−0.0006	−0.1578	−0.0280
	(0.2011)	(0.0247)	(0.0563)	(0.4297)	(0.0170)
Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year FE	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	8651	8651	8651	8651	8651
R-Squared	0.720	0.661	0.702	0.804	0.631

Note: An observation is an individual born in a rural area. Each county is matched to all weather stations within 60 km. High- and low-temperature days are defined as those with daily maximum temperatures higher than 85 °F and with daily minimum temperatures lower than 32 °F during the eight months before birth. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates for all columns. Standard errors in parentheses, clustered by county. ***Significant at 1%, **significant at 5%, *significant at 10%.

Table A.3
Different inference methods.

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp Days	−0.0157	0.0018	−0.0048	−0.0235	0.0016
-County Clusters	(0.0093)*	(0.0009)**	(0.0022)**	(0.0141)*	(0.0008)**
-Province Clusters	(0.0096)	(0.009)*	(0.0018)***	(0.0152)	(0.0009)*
-Two-way Clusters (County and Year)	(0.0092)*	(0.0008)**	(0.0023)**	(0.0137)*	(0.0009)*
-Spatial Clusters (Hsiang, 2010)	(0.0068)**	(0.0007)**	(0.0017)***	(0.0103)**	(0.0006)***
Weather & Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year FE	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	9024	9024	9024	9024	9024
R-Squared	0.715	0.657	0.705	0.796	0.620

Note: The entries after row 1 present different levels of clustering for standard errors. As our sample only has 25 provinces, we use the bootstrap method to obtain robust province-clustered standard errors (Cameron et al., 2008). In row 5, we adjust standard errors to account for the potential that disturbances have spatial autocorrelation of arbitrary form within 2000 km and serial correlation over five years (Hsiang, 2010) An observation is an individual born in a rural area. High-temperature days are defined as those with daily maximum temperatures higher than 85 °F during the nine months before birth. Weather controls include the number of low-temperature days and total precipitation during pregnancy. Demographic controls include gender, race, birth order, number of siblings, and parents' education years and age at delivery. Ordinary least squares estimates. Standard errors in parentheses, clustered by province. ***Significant at 1%, **significant at 5%, *significant at 10%.

Table A.4
Heterogeneous effect by birth place (rural v.s. urban).

Dependent Variable:	(1) Education Years	(2) Illiteracy	(3) Word-test Score	(4) Height	(5) Bottom 10% Height
High Temp X Rural Born	−0.0035	0.0008*	−0.0007	−0.0177**	0.0009*
	(0.0054)	(0.0005)	(0.0015)	(0.0076)	(0.0005)
High Temp Days	−0.0121	0.0006	−0.0040	0.0094	−0.0002
	(0.0102)	(0.0010)	(0.0025)	(0.0146)	(0.0008)
Rural Born	−4.0260	0.1813	−0.2386	−6.0474*	−0.1777
	(2.5840)	(0.1884)	(0.6615)	(3.3926)	(0.1639)
Weather & Demographic Controls	Yes	Yes	Yes	Yes	Yes
County-Year FE	Yes	Yes	Yes	Yes	Yes
County-Month FE	Yes	Yes	Yes	Yes	Yes
Year-Month FE	Yes	Yes	Yes	Yes	Yes
Observations	11249	11249	11249	11249	11249
R-Squared	0.732	0.628	0.696	0.791	0.590

Note: An observation is an individual. High-temperature days are defined as those with daily maximum temperatures higher than 85 °F. Weather controls include the number of low-temperature days, total precipitation during pregnancy, and their interactions with a rural-born dummy. Demographic controls include gender, race, birth order, number of siblings, parents' education years and age at delivery, and their interactions with a rural-born dummy. Ordinary least squares estimates for all columns. Standard errors in parentheses, clustered by county. ***Significant at 1%, **significant at 5%, *significant at 10%.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jeem.2019.01.006.

References

Almond, D., 2006. Is the 1918 influenza pandemic over? Long term effects of in utero influenza exposure in the post 1940 U.S. population. J. Polit. Econ. 114 (4), 672–712.
Almond, D., Edlund, L., Palme, M., 2009. Chernobyl's subclinical legacy: prenatal exposure to radioactive fallout and school outcomes in Sweden. Q. J. Econ. 124 (4), 1729–1772.
Almond, D., Mazumder, B., 2011. Health capital and the prenatal environment: the effect of Ramadan observance during pregnancy. Am. Econ. J. Appl. Econ. 3 (4), 56–85.
Barreca, A., Clay, K., Deschenes, O., Greenstone, M., Shapiro, J.S., 2016. Adapting to climate change: the remarkable decline in the US temperature-mortality relationship over the twentieth century. J. Polit. Econ. 124 (1), 105–159.
Barreca, A., Deschenes, O., Guldi, M., 2015. Maybe Next Month? Temperature Shocks, Climate Change, and Dynamic Adjustments in Birth Rates. NBER Working Paper 21681.
Barrios, T., Diamond, R., Imbens, G.W., Kolesár, M., 2012. Clustering, spatial correlations, and randomization inference. J. Am. Stat. Assoc. 107 (498), 578–591.
Black, S.E., Devereux, P.J., Salvanes, K.G., 2005. The more the merrier? the effect of family size and birth order on children's education. Q. J. Econ. 120 (2), 669–700.
Black, S.E., Devereux, P.J., Salvanes, K.G., 2007. From the cradle to the labor market? The effect of birth weight on adult outcomes. Q. J. Econ. 122 (1), 409–439.
Brooks, N., Adger, W.N., Kelly, P.M., 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Glob. Environ. Chang. 15 (2), 151–163.

Buckles, K.S., Hungerman, D.M., 2013. Season of birth and later outcomes: old questions, new answers. Rev. Econ. Stat. 95 (3), 711–724.
Burgess, R., Deschenes, O., Donaldson, D., Greenstone, M., 2011. Weather and Death in India. Massachusetts Institute of Technology, Department of Economics, Cambridge, United States (Manuscript).
Buxton, L.D., 2013. The Peoples of Asia. Routledge.
Cameron, A.C., Gelbach, J.B., Miller, D.L., 2008. Bootstrap-based improvements for inference with clustered errors. Rev. Econ. Stat. 90 (3), 414–427.
Cameron, A.C., Gelbach, J.B., Miller, D.L., 2011. Robust inference with multiway clustering. J. Bus. Econ. Stat. 29 (2), 238–249.
Chen, Y., Zhou, L.-A., 2007. The long-term health and economic consequences of the 1959–1961 famine in China. J. Health Econ. 26 (4), 659–681.
Currie, J., Almond, D., 2011. Human capital development before age five. Handb. Labor Econ. 4, 1315–1486.
Currie, J., Rossin-Slater, M., 2013. Weathering the storm: hurricanes and birth outcomes. J. Health Econ. 32 (3), 487–503.
Deschenes, O., 2014. Temperature, human health, and adaptation: a review of the empirical literature. Energy Econ. 46, 606–619.
Deschenes, O., Greenstone, M., Guryan, J., 2009. Climate change and birth weight. Am. Econ. Rev. 99 (2), 211–217.
Elter, K., Ay, E., Uyar, E., Kavak, Z.N., 2004. Exposure to low outdoor temperature in the midtrimester is associated with low birth weight. Aust. N. Z. J. Obstet. Gynaecol. 44 (6), 553–557.
Feng, S., Krueger, A.B., Oppenheimer, M., 2010. Linkages among climate change, crop yields and Mexico–US cross-border migration. Proc. Natl. Acad. Sci. U. S. A. 107 (32), 14257–14262.
Figlio, D., Hamersma, S., Roth, J., 2009. Does prenatal WIC participation improve birth outcomes? New evidence from Florida. J. Publ. Econ. 93 (1), 235–245.
Fishman, R., Carrillo, P., Russ, J., 2018. Long-term impacts of exposure to high temperatures on human capital and economic productivity. J. Environ. Econ. Manag. (forthcoming).
Herman, C.P., 1993. Effects of Heat on Appetite. Nutritional Needs in Hot Environments: Applications for Military Personnel in Field Operations, pp. 187–214.
Hollinger, S., Angel, J., 2009. Illinois Agronomy Handbook. University of Illinois Extension, Urbana, IL, p. 224.
Hsiang, S.M., 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. Proc. Natl. Acad. Sci. U. S. A. 107 (35), 15367–15372.
Intergovernmental Panel on Climate Change, 2013. Climate Change 2013: the Physical Science Basis.
Isen, A., Rossin-Slater, M., Walker, R., 2017. Relationship between season of birth, temperature exposure, and later life wellbeing. Proc. Natl. Acad. Sci. U. S. A. 114 (51), 13447–13452.
Maccini, S., Yang, D., 2009. Under the weather: health, schooling, and economic consequences of early-life rainfall. Am. Econ. Rev. 99 (3), 1006–1026.
Meng, X., Qian, N., Yared, P., 2015. The institutional causes of China's great famine, 1959–1961. Rev. Econ. Stud. 82 (4), 1568–1611.
Murray, L.J., O'reilly, D., Betts, N., Patterson, C., Smith, G.D., Evans, A., 2000. Season and outdoor ambient temperature: effects on birth weight. Obstet. Gynecol. 96 (5), 689–695 Part 1.
Nilsson, J.P., 2017. Alcohol availability, prenatal conditions, and long-term economic outcomes. J. Polit. Econ. 125 (4), 1149–1207.
Patel, R.R., Steer, P., Doyle, P., Little, M.P., Elliott, P., 2004. Does gestation vary by ethnic group? A London-based study of over 122 000 pregnancies with spontaneous onset of labour. Int. J. Epidemiol. 33 (1), 107–113.
Peterman, A., Ng, S.W., Palermo, T., Lee, I.-H.E., 2013. Managing the double burden: effects of pregnancy on labor-intensive time use in rural China, Mexico and Tanzania. Stud. Fam. Plann. 44 (4), 411.
Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to US crop yields under climate change. Proc. Natl. Acad. Sci. U. S. A. 106 (37), 15594–15598.
Strand, L.B., Barnett, A.G., Tong, S., 2011. The influence of season and ambient temperature on birth outcomes: a review of the epidemiological literature. Environ. Res. 111 (3), 451–462.
Wacziarg, R., Spolaore, E., 2013. How deep are the roots of economic development? J. Econ. Lit. 51 (2), 325.
Wilde, J., Apouey, B.H., Jung, T., 2017. The effect of ambient temperature shocks during conception and early pregnancy on later life outcomes. Eur. Econ. Rev. 97, 87–107.
Xie, Y., 2012. The User's Guide of the China Family Panel Studies (2010). Institute of Social Science Survey, Peking University, Beijing.
Zivin, J.S.G., Hsiang, S.M., Neidell, M.J., 2015. Temperature and Human Capital in the Short-And Long-Run. NBER Working Paper 21157.